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# LASER FLASH EFFECTS ON CHROMATIC DISCRIMINATION IN MONKEYS

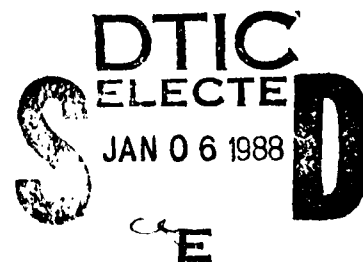Elmar T. Schmeisser, Captain, MSC, USA

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Final Report for Period April 1986 - June 1987

NOTICES

This final report was submitted by personnel of the Vulnerability Assessment Branch, Radiation Sciences Division, USAF School of Aerospace Medicine, Human Systems Division, AFSC, Brooks Air Force Base, Texas, under job order 7757-02-94.

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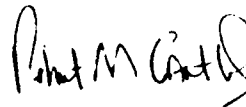
The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.


ELMAR T. SCHMEISSER, Captain, MSC, USA
Project Scientist

ROBERT M. CARTLEDGE, Lt Col, USAF, BSC
Supervisor


JEFFREY G. DAVIS, Colonel, USAF, MC
Commander

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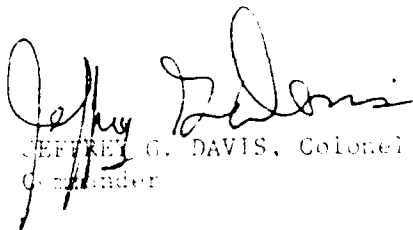
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➤Detecting a camouflaged target in a visually noisy background depends on the ability of the observer to discriminate the target from the surrounding terrain. Visual clues include size, motion, color, luminance contrast, and color contrast. It has been argued that visible laser irradiation at less than damage levels can act as a masking source by compromising or reducing the observer's ability to resolve differences in the visual scene. Previous research has examined this concept by investigating laser flash effects on: acuity (size discrimination); tracking (motion discrimination); visual sensitivity (color); and contrast sensitivity functions (luminance contrast). In all cases, flashes from continuous-wave (CW) sources have proven more effective visually than pulsed (Q-switched) sources, when compared on peak energy criterion (i.e., MPE), even though Q-switched lasers induce damage at lower energy doses. Additionally, the inherent safety of ultra-short laser pulses has been questioned. Past animal research has shown that, on the measures of acuity, sensitivity, tracking, and contrast

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## 19. ABSTRACT (Continued)

detection, the animals recover to baseline if the exposure has remained below the MPE. The one measure that has not been investigated is color discrimination, which is perhaps the most sensitive measure of suprathreshold cone visual function available.

The experiment reported here specifically investigates the comparability of shuttered CW and Q-switched visible lasers to alter and/or degrade color discrimination. Electrophysiological recordings from monkeys are used to examine the short time course effects of luminance-matched flashes from a red ruby Q-switched laser and 100-ms shuttered krypton CW laser (red, yellow, and green lines). The test target was a shifting pattern of alternating luminance-matched 510- and 550-nm green bars. With flashes equated to 4.5 log td-s, similar flash effect curves were seen, demonstrating a 1.5-s reduction in response magnitude. This level of flash did not produce a total obscuration of the target. The decrement curve was "W"-shaped, with the intermediate recovery peak occurring at approximately 500 ms after the flash and exceeding the baseline response level. The hypothesized mechanism for this result is an induced luminance imbalance caused by a transient shift in the peak color responsiveness of the visual system, which recovers with two different time constants. The perceptual equivalent might be imagined to be a change after the flash from a colored pattern to a more grey one, which then fades again until it recovers to a chromatic pattern.

The major conclusions from this investigation are: (a) red and green colored laser flashes shift the color balance transiently in the visual system, and yellow flashes do so to a lesser extent; thus targets may change both hue and brightness after an observer receives colored flashes; and (b) Q-switched lasers, at non-lesioning levels, when equated for time-averaged perceptual brightness, have comparable effects to flashes with longer time courses.

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# LASER FLASH EFFECTS ON CHROMATIC DISCRIMINATION IN MONKEYS

## INTRODUCTION

While color displays are being used to an increasing extent within cockpits to convey critical information, out-of-cockpit target detection will be even more critically influenced by the operator's ability to distinguish small differences in color. Induced disturbances of color vision may produce an unacceptable increase in workload, as the operator tries not only to interpret the information presented by instruments but also to discriminate camouflaged targets from their relatively matched backgrounds. In-band (visible) laser radiation may provide such an induced disturbance. Lasers produce light with very specific and unique properties: temporal and spatial coherence; extreme collimation; extreme monochromaticity; and (in some systems) ultrashort (20-ns) pulses with very high peak powers. With laser wavelengths available in the visible spectrum, this situation results in a specific potential threat to visual function. In the military context of laser rangefinders and target designators, this threat may be a significant problem for pilots and other military personnel on the modern battlefield (1-3).

Targets can be discriminated from their backgrounds by contrast, color, texture and/or relative motion. As a consequence, the visual functions that must be optimal for good target acquisition are: dynamic acuity, chromatic acuity, contrast sensitivity, and chromatic discrimination (4,5). A limiting case of the first three functions is normally measured by Snellen acuity (high negative contrast static target discrimination in broad-band white light). In the case of a camouflaged ground target, the only discriminable information may be a difference in hue (e.g., the green of a plastic net vs. the green of natural foliage), since other cues will have been minimized by breaking up the target outline, remaining still, and minimizing luminance differences against the surrounding terrain.

As already indicated, one of the fundamental abilities of the primate (including human) visual system is the discrimination of one color from another (6). Current models of color vision are generally based on the assumption that the responses from three types of cone receptors in the retina (commonly called red, green, and blue cones) are processed into separate "chromatic" and "achromatic" information channels (7). These channels balance the activities from the receptors to provide the perception of many colors. The achromatic system is sensitive to luminance differences (brightness), while the chromatic system apparently is tuned to detect differences in hue (8).

Perceptual changes can occur as a function of previously experienced colors, since both the chromatic and achromatic channels display adaptation effects produced by colored fields (9). In the achromatic system, these effects are reflected by changes in the luminosity function (just detectable amount of light as a function of wavelength) (10,11). In the chromatic

system, the adaptation effects appear as changes in the wavelength difference needed to discriminate two colors. In general, at moderate levels of long-term adaptation to a specific wavelength, absolute sensitivity to that wavelength is worsened while relative hue discrimination near that wavelength is improved. However, the discrimination at the complementary wavelength is degraded also (12).

Visual color mechanisms, while tuned optimally to certain ranges, can respond to all colors. Therefore, it is important to note that the general trends determined with localized (foveal) threshold stimuli (reported in the foregoing paragraphs) have been observed to break down at high luminances and with small, brief stimuli such as could be produced by lasers (13,14). At suprathreshold levels, chromatic and achromatic mechanisms interact, producing nonlinear effects. As luminance levels rise, spectral sensitivity curves become more complex, and adaptation bandwidths broaden. Even more complex behavior can be demonstrated when colored targets are measured against colored backgrounds. Using extremely short and bright flashes to chromatically adapt the visual system might produce responses that are not predictable from a linear extrapolation of the data from experiments using more moderate lights.

Because of the lack of data, monkeys have been the animal of choice in laser bioeffects studies, when the energies are such that human volunteers ethically cannot be used. The visual system of the monkey has been shown histologically, anatomically, electrophysiologically, and (within certain constraints) psychophysically, to closely parallel the human (15-17). To date, work on laser flash effects has been concentrated on acuity shifts and changes in contrast sensitivity, which are functions predominantly of the achromatic visual system (18-21). Additionally, some data have been developed with retinal ganglion cell recordings in monkeys (22,23). In these experiments, exposure to single Q-switched pulses of frequency-doubled neodymium laser light resulted in reversal of the color specificities of the ganglion cell's receptive field organization, thus indicating that the substrates for color specific alterations can be found at the unit level. Global chromatic functions such as color discrimination have not yet been examined, however.

The visual evoked potential (VEP) is an electrical signal produced by the visual cortex in response to some change in the stimulus to the visual system; i.e., a stimulus-synchronized time-averaged electroencephalogram. VEPs have been recorded to both flickering and/or flashing lights, and shifting patterns of light and dark bars (15). By replacing the bars in a grating type of display with alternate colors, one can evoke a response that depends on the wavelength difference between the bars. Further, by selecting a criterion amplitude (or latency) of the VEP, one can produce a wavelength "discrimination" function closely parallelling that determined psychophysically (15,24). Additionally, selective (wavelength specific) chromatic adaptation (i.e., changes in the chromatic discrimination function) has also been demonstrated by VEP (10,25). Therefore this signal seems to be an appropriate objective metric of changes in color vision reported by human observers, and can provide the bridge between monkey and human data. These experiments were therefore undertaken to determine the

effects, if any, of both short and long pulses of visible laser light on chromatic discrimination, as measured by changes in the VEP.

The set of experiments detailed in this report are part of a complete experimental matrix of flash parameters involving spot size, laser color, pulsewidth, and stimulus color (Table 1). The exact parameters selected were those which were felt to be the most likely to generate the largest and hence most easily measurable effects. That is, a stimulus was selected near the peak of the visual response curve, a spot size was selected that completely covered the stimulus, the color dependency was assayed with long pulse exposures, and the pulse dependency was assayed at a single color (red).

TABLE 1. LASER FLASH EXPOSURE AND TEST WAVELENGTH MATRIX*

| LASER PARAMETERS | FLASH NM | REFERENCE WAVELENGTH | | |
|---|---|---|---|---|
| | | 532 NM | 568 NM | 670 NM |
| 100 MS | 531 | (A)(B) | | |
| 5 DEG SPOT | 676 | (B)(C) | | |
| 100 MS | 531 | | | |
| MIN SPOT | 676 | | | |
| 20 NS | 532 | | | |
| 5 DEG SPOT | 694 | (A)  (C) | | |
| 20 NS | 532 | | | |
| MIN SPOT | 694 | | | |

| FLASH | REFERENCE 532 NM |
|---|---|
| 568 | (B) |

A : Preliminary experiment (heterochromatic flicker stimulus)
B : Flash wavelength comparison experiment (pattern stimulus)
C : Flash pulse length comparison experiment (pattern stimulus)

*The 8 by 3 matrix shows the experimental design of laser flashes, with 2 spot sizes, 2 colors, and 2 pulse durations crossed with 3 test wavelengths (red, yellow, and green) used to set up the VEP stimulus on which the flashes would be superimposed. The three experiments reported in this paper are indicated by the circled letters (A), (B), and (C).

## METHODS

The goals of these experiments, in monkeys, were as follows: (a) to determine a VEP tuning curve as a function of chromatic difference, using optical methods to counterphase light patterns derived from monochromators; then; (b) to select a VEP criterion amplitude (implying a specified chromatic contrast; i.e., delta lambda in the stimulus); (c) with this test stimulus driving the VEP, to superimpose an "eye-safe" (sub-MPE) visible wavelength laser flash; and (d) using a vector voltmeter and a signal averaging computer, to measure the (presumed) drop and recovery of the VEP as a function of time.

Apart from the tuning curve (discussed later), one preliminary and two major experiments were performed, differing both in their stimulus methodology and their flash parameters (Table 1: items A, B, and C).

### Stimulus System

The preliminary experiment used the stimulus system shown in Figure 1*. The white light beam from an Oriel 1 kW xenon arc lamp source was focused on an aperture, recollimated, heat filtered, and split into two beams. Each beam was passed through neutral density filters and a monochromator. The beams were recombined on the surface of a rotating Plexiglas disk. This disk had a vacuum-deposited aluminum mirror coating over one half of its surface, thus providing an alternating stimulus beam to the camera port of a Zeiss fundus camera. This beam was passed through a 5-deg aperture and through the fundus camera in Maxwellian view into the experimental subject's eye. The resulting stimulus was a heterochromatic, luminance-balanced flicker whose wavelength, luminance level, and temporal rate were all independently controllable. Due to inhomogeneities of the Plexiglas substrate and of the mirror coating, a strong luminance artifact at both the onset and offset of the mirror edge, as well as a ramped luminance change during the rotation of the mirror segment, was unavoidable. Therefore, the data from this experiment were kept separate from the remainder.

The two major experiments used a system taken from Petry et al. (24) and diagrammed in Figure 2. The rotating mirror-disk was replaced by another beamsplitter cube, thus recombining the beams. In each collimated path before this cube, a 50% duty cycle black and clear grating was so placed that, upon recombination, alternate stripes of the resulting square-wave grating pattern would derive from each monochromator separately. The recombined beam was focused on a mirror galvanometer, then reimaged onto the camera plane of the fundus camera as before. An aperture in this plane limited the pattern size to 5 deg on the retina. The spatial frequency of the pattern was 1 c/deg. Temporal modulation in all experiments was 6 square-wave stimulus transitions/second. Luminance calibration (Pritchard model 1980B-PL spectrophotometer) showed both the flicker beam and the pattern brightness to be 2.8 log td (approximately normal daylight level).

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*EDITOR'S NOTE: For the convenience of the reader, all figures have been grouped at the close of this report.

## Flash Sources

Two lasers served as the flash sources: a continuous wave Coherent CR750K krypton ion gas laser; and a Lasermetrics xenon flash-pumped, Q-switched ruby pulse laser. The krypton laser was tuned to give 100-ms shuttered flashes of either 676, 560, or 530 nm. The ruby laser produced 20-ns flashes of 694-nm light. These flashes were delivered by a beam-splitter between the fundus camera and the cornea in Maxwellian view. The flashes covered a 5-deg retinal irradiance diameter coextensive with the stimulus area. The laser sources were all made equal to 4.85 log td-s. Calibrations were performed with an EGG model 165 microwatt-meter (krypton laser), and a Laser Precision Rj-7200 joule-meter (ruby laser). Reference detectors used to monitor the lasers during the experiment itself were: a Photodyne 66XLA optical power meter with integrating sphere head (krypton laser); and a Scientech model 365 integrating energy meter.

## Animal Preparation

VEP electrodes were surgically implanted in a separate procedure before any testing was performed. Three rhesus monkeys (Macaca mulatta) were anesthetized, intubated, and surgically prepared as per standard operating procedures in the USAF School of Aerospace Medicine (USAFSAM) Veterinary Sciences Division (previously described (20)). Modifications of this technique for two further monkeys, also implanted, are described here: under sterile conditions, the scalp was opened with a midline incision, and the cranium cleaned of adherent tissue. Two stainless steel anchor screws were implanted in the skull to hold the final appliance. Circular apertures, 1 cm diam., were drilled in the skull over each visual cortex (approximately at 22 mm lateral to the midline and 12-15 mm posterior to ear-bar zero), and shaped to fit looped methylmethacrylate (Plexiglas) windows. The dura was incised and removed from these apertures. After visual inspection of the cortical surface to insure avoidance of all blood vessels and cortical sulci, the windows had small electrode channels drilled in them and were cemented in place with cold-cure dental acrylic.

Transcortical bipolar electrodes were especially constructed by Rhodes Medical Instruments (Woodland Hills, CA). These electrodes, which were made of stainless steel and insulated with epoxy resin, had one wire 3 mm longer than its mate. The longer electrode also had 1/2 mm of its tip stripped of insulation and electrolytically sharpened. Each bipolar electrode was lowered by a stereotaxic apparatus through an electrode channel of the Plexiglas window until visual confirmation of penetration of the cortex to a depth that just permitted the shorter (reference) electrode to touch the cortical surface. The electrodes were connected to a Grass EEG amplifier, and were tested for activity in response to a light flash produced by a xenon flash photostimulator directed at the respective animal's eyes. Replacement or modification of the electrodes' position was undertaken until single flash VEPs of at least 50 $\mu$V were obtained. The electrodes were then cemented in place, connected to a Winchester plug, and the entire assembly (including wires) was carefully covered with dental acrylic. Generally, two bipolar electrodes were implanted in each hemisphere. The animal's scalp was then approximated around the plug and sutured. After recovery, the

animal was returned to the colony for a minimum of one week, and was held until called for by the experimental protocol. A course of steroids (chloramphenicol 50 mg/kg BID x 10 days) and antibiotics (dexamethasone 0.25 mg/kg x 5 days) was given to control brain edema and any possibility of infection.


## Recording

The animal was sedated with ketamine (15 mg/kg), anesthetized with pentobarbital (15 mg/kg), intubated, and catheterized in a hind-limb vein. Continuous monitoring of body temperature, percent ventilatory $CO_2$ (Beckman LB2), and heart rate (ECG) was established. Values were maintained within physiological limits (35-37°C, 4-5% $pCO_2$, and 120-180 BPM). The animal's ventilation was assisted with a Harvard small animal respirator; rate and depth were titrated to maintain the appropriate $pCO_2$ level throughout the experiment. The animal was muscularly relaxed with a bolus of gallamine triethiodide (Flaxedil: 3 mg/kg), wrapped in a heat blanket, and placed on a padded rotating stage in front rf the fundus camera. The head was held in place either by foam pads and tape or by non-traumatic earbars. The pupil was dilated with ophthalmic atropine drops (1%), the lid retracted with a light wire speculum, and the cornea protected with a hard contact lens. The animal's fovea was aligned on the optical axis of the fundus camera and focused. The camera film plane was therefore conjunct to the retina, and any image at that plane was in focus on the retina. The stimulus was presented to the animal by deflecting the fundus camera eyepiece switching mirror.

The EEG was recorded between the tips of each bipolar electrode and amplified by Grass 7P511J EEG amplifiers (bandpass: 1-100 Hz with 60-Hz notch). The signals were recorded on FM tape for archiving and later analysis if needed. The EEG was then either averaged directly on a Norland digital averaging oscilloscope to produce calibration VEPs, or passed to a PAR vector-voltmeter in order to perform an on-line analog Fourier extraction of the stimulus response signal magnitude. The magnitude readout was passed to the Norland for averaging across flashes during the laser exposures. All averages were downloaded to a PDP 11/03 computer for digital storage. Selected averages were then passed to a Zenith Z100 computer for amplitude analysis and plotting. Peak values and ratios were entered into a two-way ANOVA (monkey vs. flash condition) in the RS-1 program on a microVAX II computer, and analyzed for significance.


## Procedure

As just mentioned, one of three types of session was run: a color tuning curve, a 3-color krypton flash effect test, or a Q-switched ruby vs. long-pulse krypton flash effect comparison.

## Color Tuning Curve

In this run, no flashes were superimposed on the stimulus pattern, and the data consisted of the amplitude of the averaged VEP to each stimulus. One monochromator was locked to one of three wavelengths (510, 580, or 660 nm); and the other was scanned in overlapping ranges from 440 to 680 in 20-nm increments. The neutral density filters were adjusted so that both the mean luminance and the luminance balance of each pair were preserved. Steady-state VEPs from two electrodes were taken for each luminance balanced wavelength pair. These values were normalized to the individual electrode's maximum response (luminance stimulus: black and green grating, or green ON-OFF flicker), and averaged. From the resulting curves, the criterion level of 30% maximum VEP was selected. This level should be below any saturation of the response which could mask response changes, but still sufficiently large to permit easy recording (26). The 30% criterion response level implied a 40-nm chromatic difference in the channels. For the flash-effects sessions, therefore, a 510+550 color separation was chosen.

## Three-color Krypton Laser Flash Effect Test

All three color flash testings were done with the pattern stimulus. The 510+550-nm grating pattern stimulus (just described) was projected onto the retina. With a steady-state VEP being monitored by the vector-voltmeter (VVM), a series of ten 100-ms, 5-deg flashes were superimposed on the stimulus at 20-to-30-s intervals, random in respect to the grating shift. The magnitude readout of the VVM from these 10 epochs was averaged. The wavelength of the krypton laser was then changed and adjusted in brightness, and the second set of flashes delivered and separately averaged. In a similar manner, the third wavelength was assayed for its flash effect on the VEP evoked by the 510+550-nm stimulus. The three laser-flash wavelengths (531, 568, and 676 nm) were taken randomly, in either an ascending or a descending series, across the five animals tested.

## Ruby vs. Krypton Flash Effect Comparison

The preliminary run, comparing krypton green (100 ms, 530nm) with ruby red (20 ns, 694 nm), was performed using the heterochromatic stimulus. The succeeding runs compared krypton red (676 nm, 100 ms) with the ruby red exposure, and used the counterphasing chromatic grating stimulus. The same stimulus parameters were used as before (510+550 nm, 5 deg, foveal, 6 shifts/s). The krypton flash was assayed first, as its beam required the use of a beam telescope to achieve the required image diameter. This beam telescope was then removed from the optical path for the ruby exposure. Both flash sources had been previously calibrated, and had been made photometrically equal (4.85 log td-s). This level was insured by use of the reference detectors during the runs.

All experimental runs were complete in 2 h, and the animal allowed to recover. When it was conscious and able to sit in its cage, the animal was returned to the colony. Retesting was not performed at intervals of less

than one week and, generally, more than two weeks elapsed between runs for
the same animal.


## RESULTS

### Chromatic Tuning

Color tuning curves obtained from one animal (two electrodes) with the
pattern stimulus are depicted in Figure 3. Curves obtained with the
heterochromatic flicker stimulus from a different animal were similar in
shape, but flatter in amplitude (noisier). These curves show a wavelength
tuning similar to the human color discrimination function, in that both the
green and yellow regions show the sharpest tuning, and thus the smallest
just-noticeable-difference, while the red region is broader. Best
performance is near the peak of the luminance response function, near
yellow.


### Wavelength Dependence

The effect of three wavelengths of 100 ms, 5-deg krypton laser light,
on the 510+550 pattern stimulus is shown in Figure 4. The traces have been
normalized for each monkey, individually, to his pre-flash VEP level, and
then averaged across five animals. A large post-flash rise in signal
strength, which can be seen in the second after the flash, is followed by
a mild decrement below pre-flash levels which recovers by 4 s after the
flash. The red (676-nm) and green (530-nm) flashes show no significant
difference; but the yellow (568-nm) flash peak is more than 2 standard
errors of the mean below their level. Shown in Figure 5 are the mean and
2 s.e.m. of the ratios of the induced luminance peak ratios; the analysis of
variance showed a significance level of p=0.006 for flash condition
difference.


### Pulse Length Comparison

Shown in Figure 6 are the traces obtained by both ruby (694-nm, 20-ns)
and krypton green (530-nm, 100-ms) flashes placed on the luminance
contaminated heterochromatic flicker stimulus. Both the decrement and the
induced signal rise can be seen in the traces, with the red flash having
slightly greater effect in both components than the green. No analysis was
performed on the data from this one monkey.

Shown in Figure 7 are averaged, individually normalized traces (from
five monkeys) using the pattern stimulus, and comparing krypton red (676-nm,
100-ms) to ruby (694-nm, 20-ns) flashes. These traces show similar profiles
to the three-color experiment just reported. Additionally, the ruby flash
induced a slightly higher, although not statistically significant, post-
flash peak than the krypton (p=0.674 for peak ratios), even though the
flashes had been photometrically balanced.

# DISCUSSION

The major finding of an increase in stimulus strength over baseline during the flash-effect period implies not only that the stimulus has not been masked out by a possible afterimage, but that it has become transiently more visible. The comparison of the results, seen with the luminance artifact contaminated stimulus and the luminance-artifact-free pattern stimulus, indicates that a possible explanation could be provided by selective chromatic adaptation of the "red" and "green" mechanisms and the resulting induction of a luminance signal; i.e., a luminance imbalance of the previously balanced stimulus, due to a change in the relative balance of the chromatic channels involved.

A possible mechanism is diagrammed in Figure 8. In each panel, two pairs of curves are shown, as are both the stimulus and flash wavelengths. The top curve of each pair is the response of the visual system to the 510-nm channel in the stimulus system; the other member is the 550-nm channel response, which has been lowered by neutral density filters. Thus, the horizontal lines point out the luminance component of the resulting heterochromatic stimulus (for the pre-flash curves, none). After either the ruby 694-nm or the krypton 676-nm flash, the response curve of the visual system not only drops in absolute response level, but also shifts its peak sensitivity away from the flash wavelength, presumably by selective adaptation of the red-sensitive mechanism more than the green; i.e., to curve POST. Since the stimulus wavelengths have remained the same, there is a resulting luminance difference between the two halves of the stimulus, indicated by the split horizontal lines labelled (A). The 532-nm flash shifts the curve in the right panel, and induces a luminance imbalance shown by the label (C).

In the case of a psychophysical "unique yellow" flash, the curve will not shift laterally (by definition), but will simply drop vertically due to equal adaptation of both the red and green mechanisms (middle panel), producing no luminance imbalance (10). As a result of the induced luminance imbalance, the visual system is driven by a highly enhanced luminance signal as well as by a reduced chrominance signal. Because the VEP gives a greater response to luminance gratings than to luminance balanced chromatic gratings, this component would provide the stimulus necessary to drive the response signal above baseline. Support for this hypothesis is given by the observation that the krypton yellow flash produced a smaller induced peak than either the red or green flashes, and that the green flash response was slightly smaller than the red flash. In addition, the ruby flash, which is 20 nm more red than the krypton wavelength, is slightly stronger. Recovery of the achromatic system is also faster than recovery of the chromatic system; and, as the former recovers, the luminance component of the stimulus will also decay. Thus, the response data show only a transient peak before decaying to slightly below baseline and, finally, completely recovering.

Previous work (27) at higher flash levels, using colored gratings, has failed to show either wavelength dependence or luminance signal induction. The flash levels used in those experiments were 3 log units brighter than those in this work, and might be expected to so completely suppress the luminance system that these relatively fast events would be unrecordable.

Psychophysical work (28,29) has shown that luminance "flashblindness" does not occur before 5.5 log td-s, and saturates at 7.5 log td-s. The low flash levels used in this set of experiments (4.8 log td-s) may be the greatest at which these effects can be demonstrated. The picture that emerges then unifies the data so that, at low flash energies, the only effect is simultaneous masking; at higher energies, selective adaptation can induce changes in the target that could enhance its detectability. At higher energies, the non-selective adaptation can only depress detection. At even higher energies, damage mechanisms supervene, and permanent scotomata can result.

Finally, the data seem clear from this study as well as others (already cited) that the visual system does not process 20-ns light flashes in any special way. The data from the direct comparison between long pulse green flashes and short pulse red flashes indicate that qualitatively similar selective chromatic adaptation occurs when the flashes are equated photometrically. All other conditions in the original matrix (e.g., minimal spot size, stimulus farther into the red, etc.) will have smaller effects, and thus can be extrapolated to be of less importance to normal visual performance (18-20).

Data produced by these experiments also bears on the extrapolation of the maximum permissible exposure (MPE) levels for Q-switched visible lasers from criteria based on ophthalmic damage to criteria based on functional decrements in vision. Past work in primates (cited in the "Introduction") has shown that acuity, contrast sensitivity, and threshold light detection recover to baseline after exposures at or below the MPE. A visual function that has not been analyzed is chromatic discrimination, which is perhaps the most sensitive to cone integrity. Since this function demonstrated recovery, from Q-switched flashes, that was not significantly different from that seen with longer flashes, exposures in human volunteers could be undertaken with the expectation of minimum risk of lasting damage.

## CONCLUSIONS

Color disturbance effects produced by visible lasers are small, and will probably not significantly impact target acquisition except in very rare visual circumstances (completely luminance-balanced scenes). Such color effects may even enhance target acquisition, although both target hue and brightness may change. The major impact of any visible laser exposure will be on the luminance system.

Visual effects produced by Q-switched lasers are predictable from exposures produced with longer pulsewidths, provided that the irradiance levels are expressed in photometric units and that damage mechanisms do not intervene.

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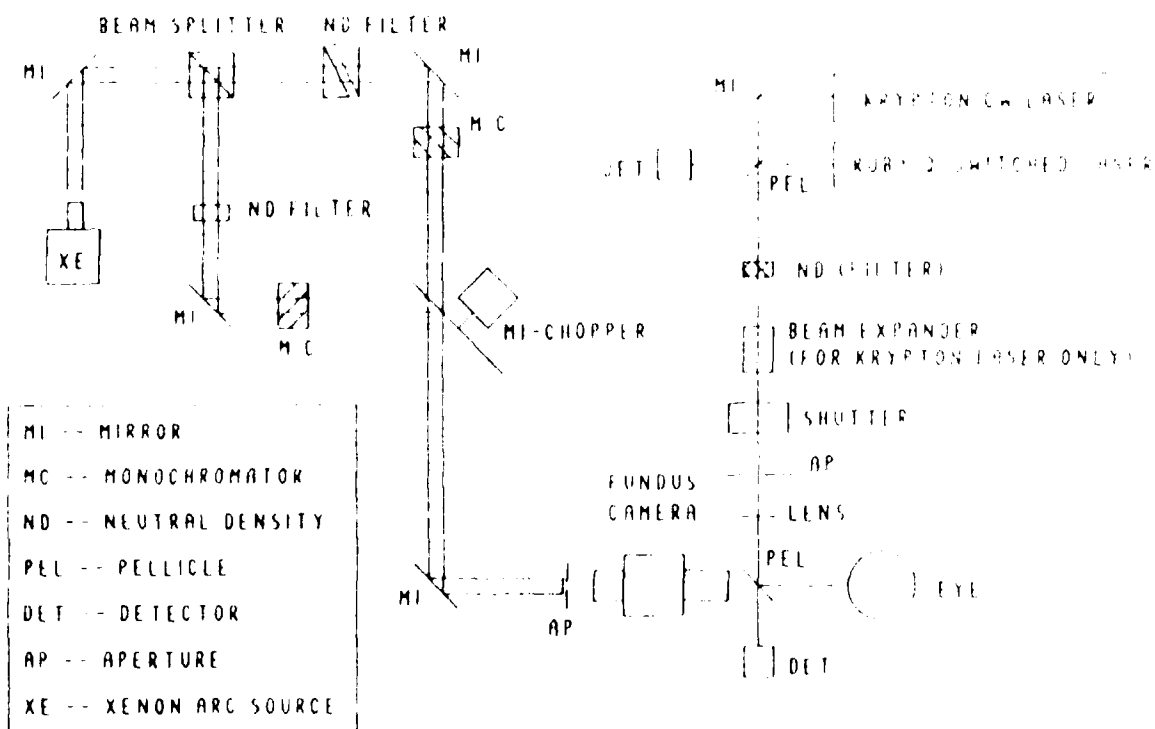
F I G U R E S

Figure 1.   Stimulus system:   rotating mirror.

A light beam is taken from a xenon arc source, split, chro-
matically filtered, and luminance balanced.   Each of the split
beams is then alternately passed to the fundus camera film plane
and thus into the subject's eye.   The selected laser beam is
superimposed onto the stimulus in Maxwellian view by the pellicle
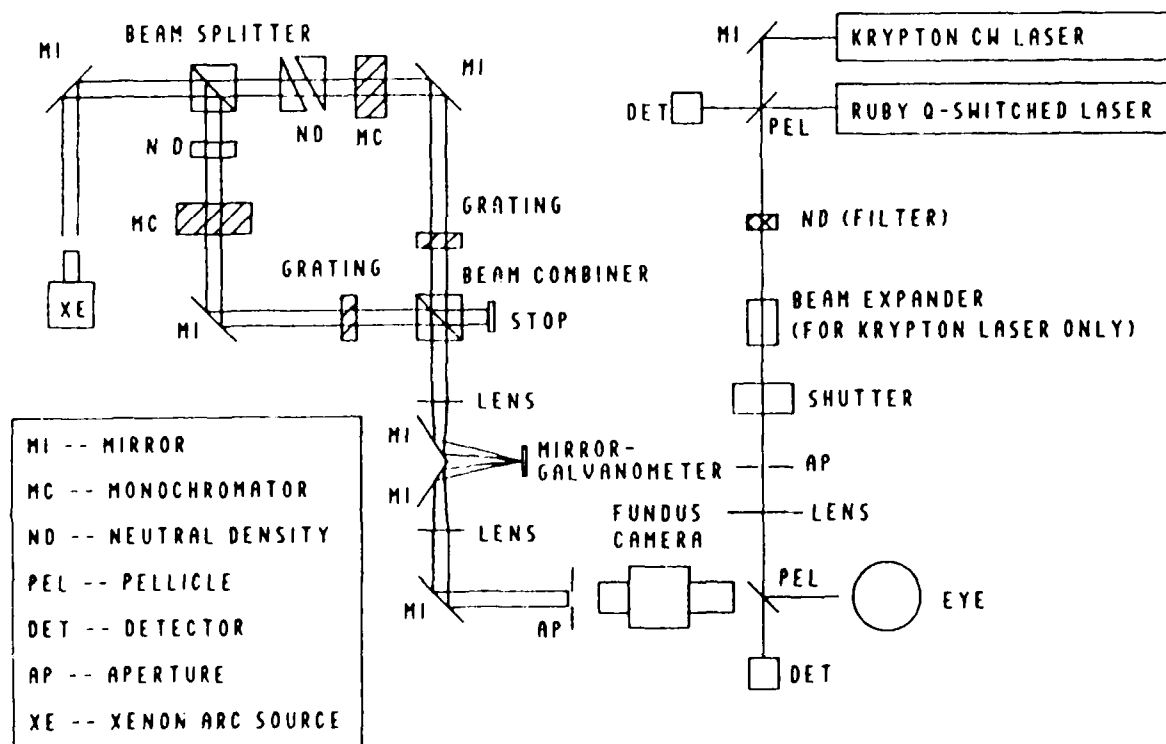beamsplitter.

Figure 2. Stimulus system: counterphasing pattern.

The mirror chopper in Figure 1 is replaced with a lens and mirror
galvanometer arrangement, and clear and black gratings are placed
in the split beam paths to produce a shifting, heterochromatic
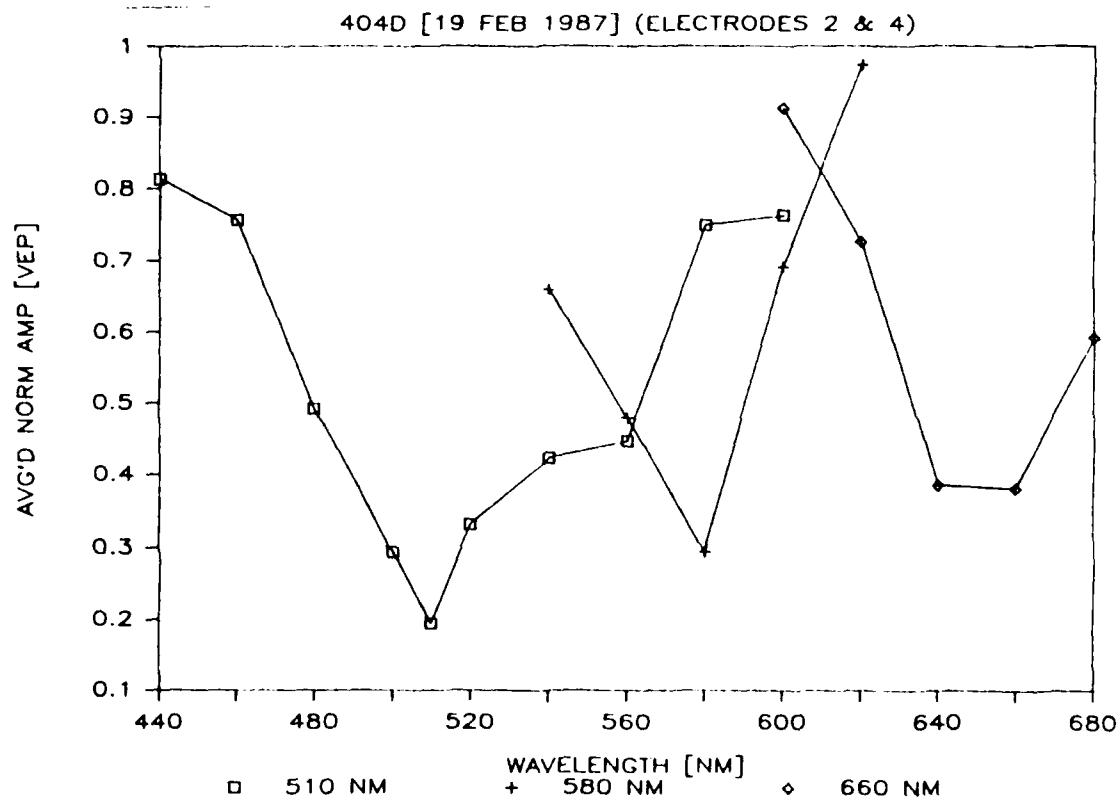grating. (Otherwise, as in Fig. 1.)

**404D [19 FEB 1987] (ELECTRODES 2 & 4)**

□ 510 NM     + 580 NM     ◇ 660 NM

Figure 3.  Chromatic difference tuning curve.

Response amplitudes of VEPs elicited with gratings at discrete
wavelength differences.

Three tuning curves demonstrate signal extinction when both
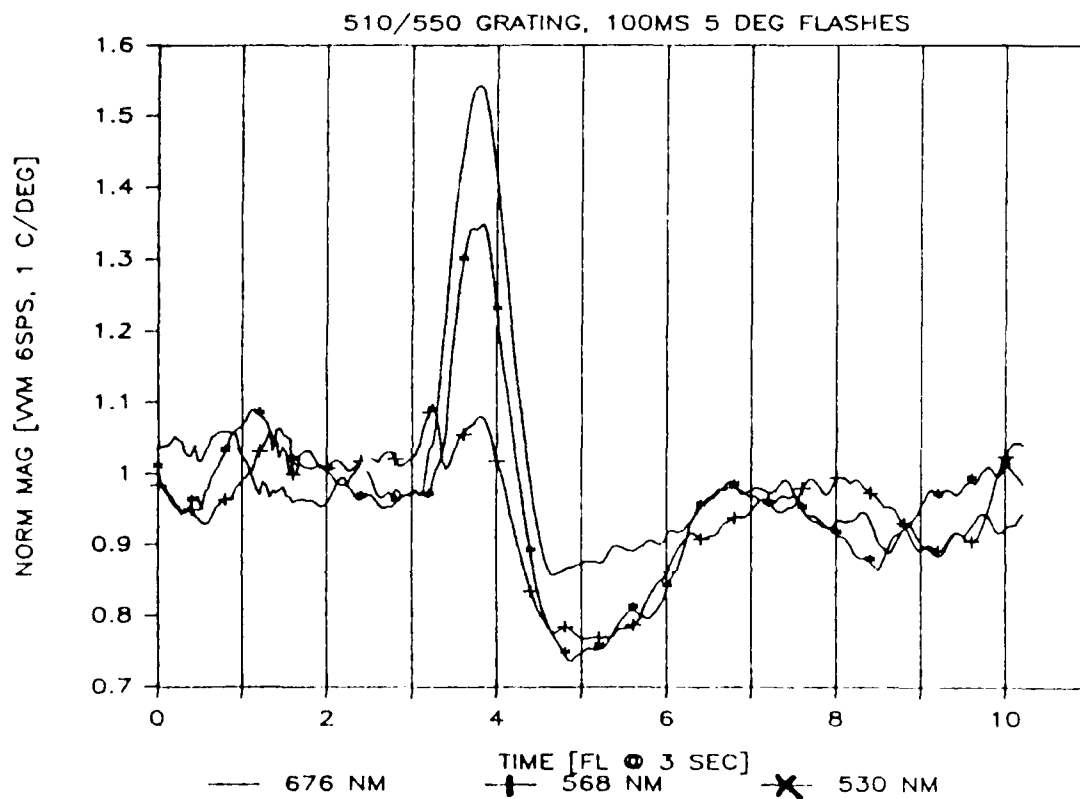sets of pattern stripes are closely matched in wavelength.

16

Figure 4. Flash wavelength comparison.

Five monkey average of vector-voltmeter magnitude output. The induced magnitude peaks rank (largest to smallest) red, green, and yellow. Red and green are not significantly different; the yellow peak is more than 2 s.e.m. below these.
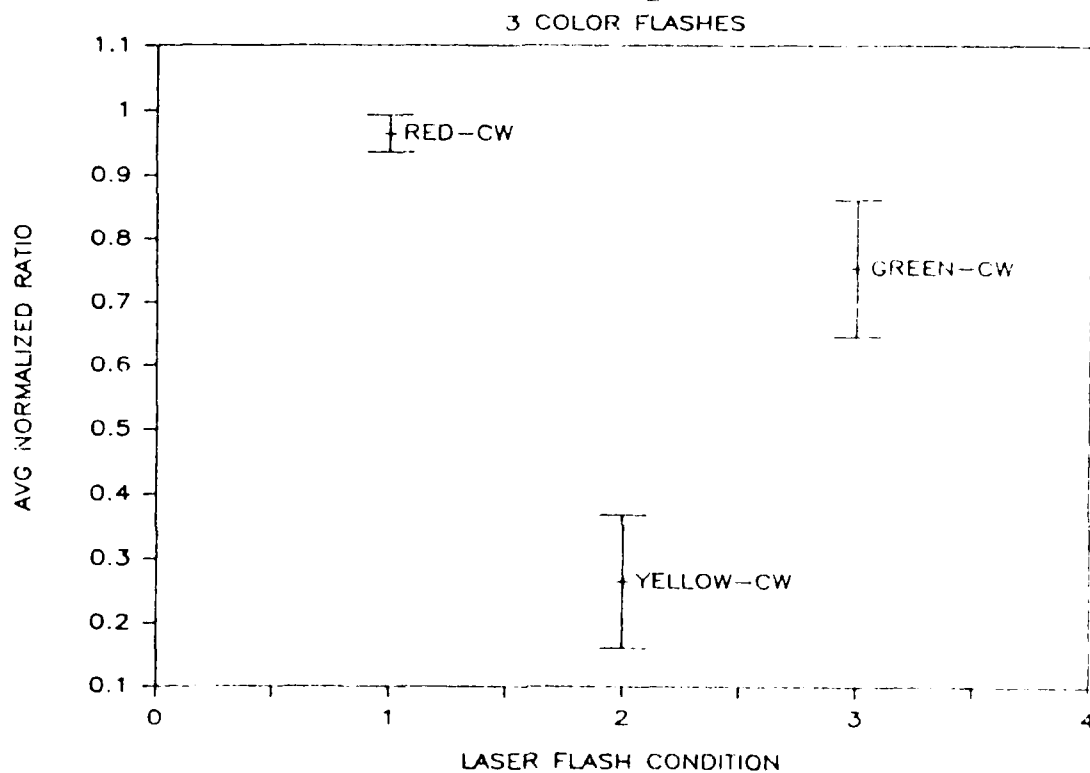
Figure 5. Averaged induced luminance peak ratios.

Means and 2 standard errors of the mean of the ratios of the induced peak heights for 5 monkeys, showing that the yellow flash produces a significantly lower luminance peak than the peaks induced by either the red or the green flashes.

510/550 NM HETEROCHROMATIC FLICKER
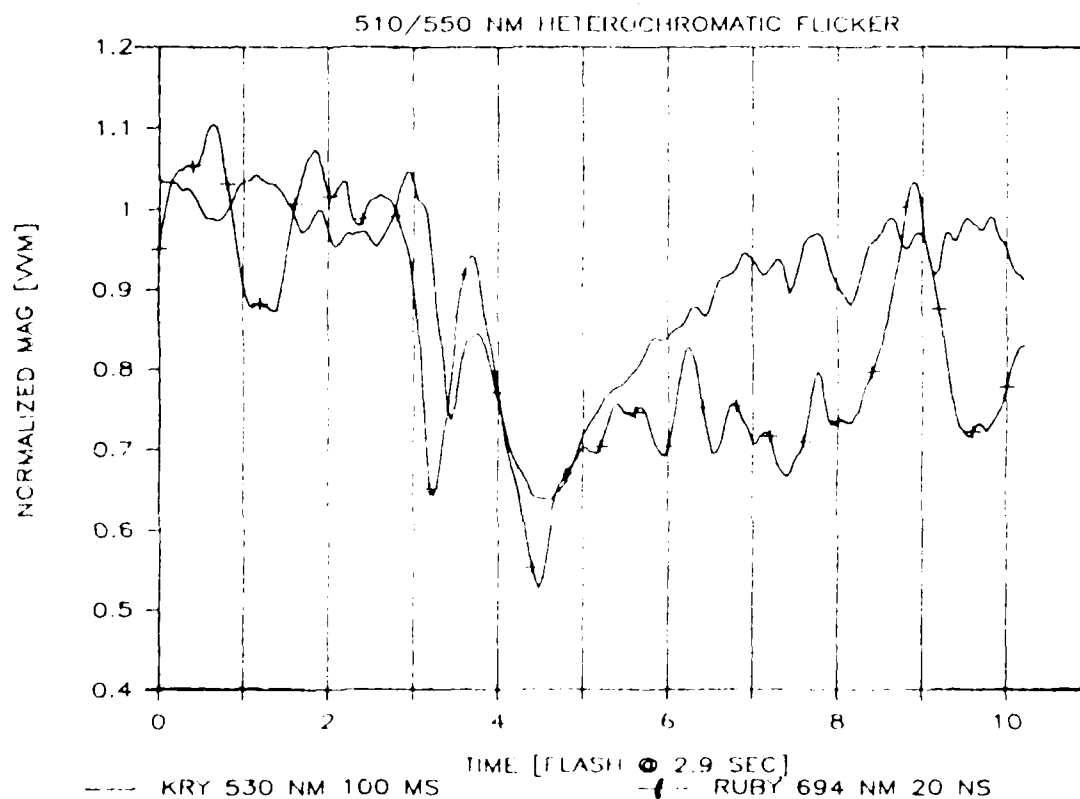
KRY 530 NM 100 MS          RUBY 694 NM 20 NS

Figure 6.  Flash pulse-width comparison:  Heterochromatic flicker.

Vector-voltmeter magnitude readout from one monkey.  A krypton
green flash and a photometrically equivalent Q-switched ruby
red flash are compared.  A two-component decrement and recovery
curve is demonstrated.  The curves display no qualitative
difference in shape or time course.  The induced peak is also
smaller than in the cases using the pattern stimulus, due to the
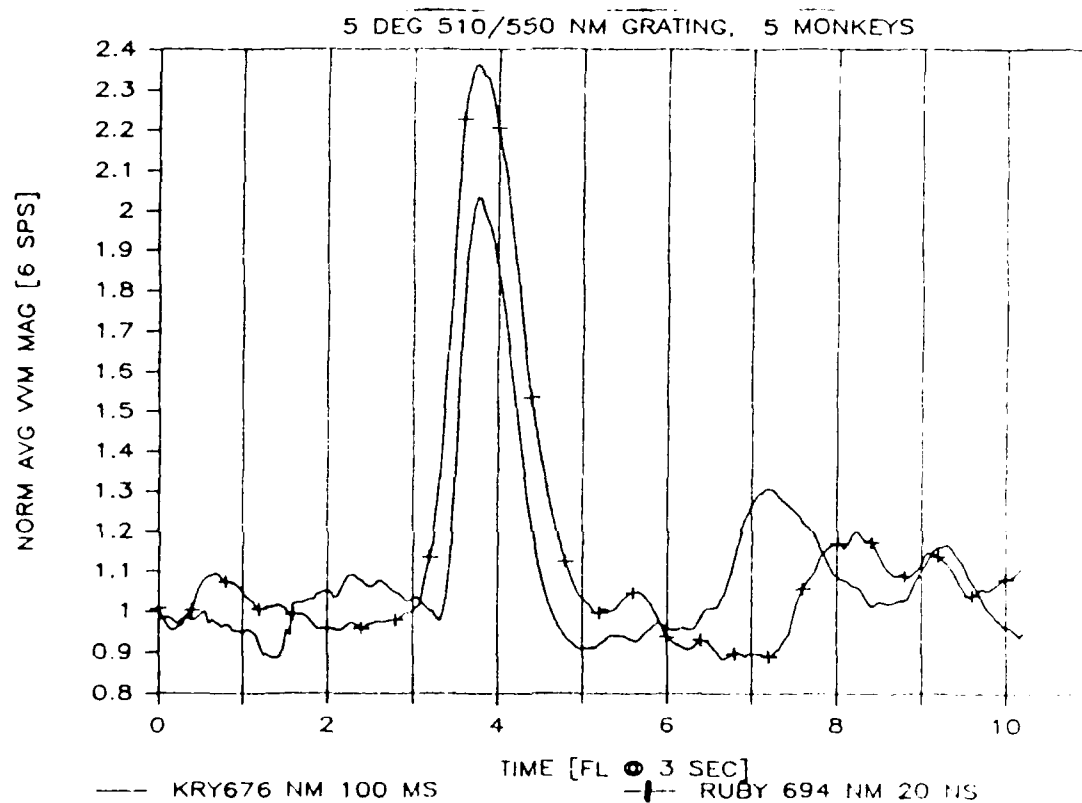luminance artifact of this stimulus system.

Figure 7.  Flash pulse-width comparison:  Heterochromatic grating shift.

Five-monkey average of ruby red and krypton red flash effects.
The ruby flash shows a greater though not significant luminance
induction than the krypton flash.

**RED FLASH** — **YELLOW FLASH** — **GREEN FLASH**

(A) & (C): FLASH INDUCED CHANNEL IMBALANCE

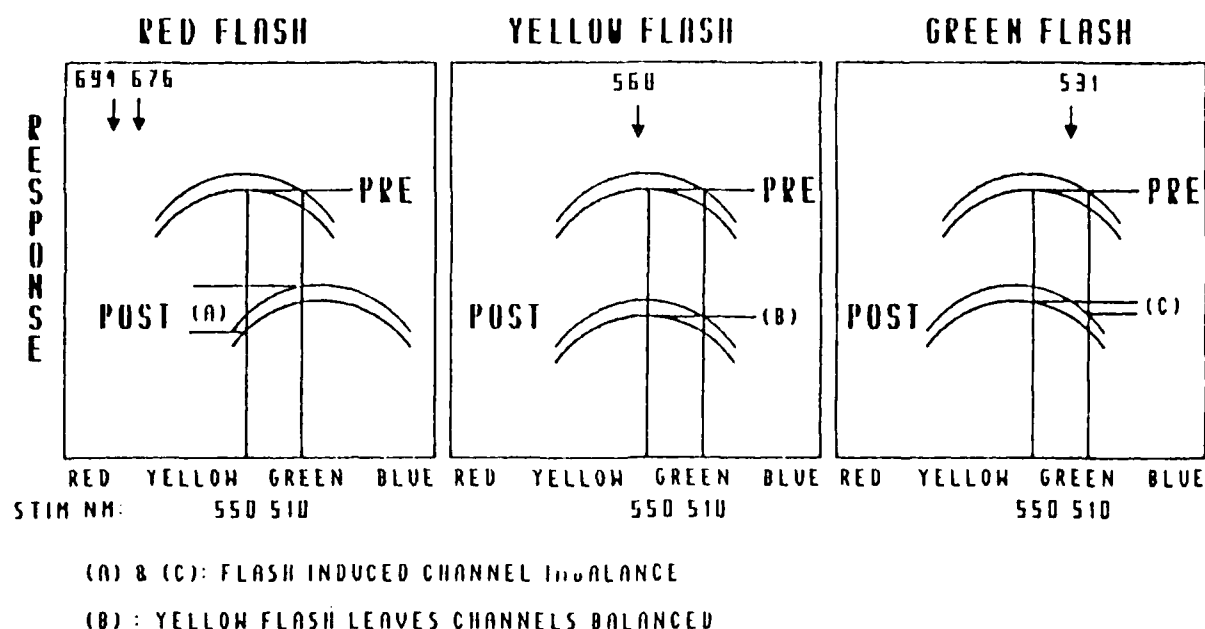(B) : YELLOW FLASH LEAVES CHANNELS BALANCED

Figure 8. Hypothesized mechanism for luminance signal induction.

Graphs of the VEP chromatic response curves of the visual system. Each member of the paired curves refers to one channel of the stimulus apparatus. The horizontal lines indicate the luminance balance (or imbalance) of the stimulus (510+550 nm). Curve pair labelled PRE: preflash baseline, luminance difference is 0; left panel, lower pair: response profile after preferential adaptation of the green mechanism by the krypton 531 flash, with induced luminance difference (A); right panel curve: response profile after adaptation by either the ruby or the krypton red flashes (for simplicity shown as the same curve; they may be slightly shifted) (C); middle panel curve pair: ideal response curve after adaptation by "unique yellow," approximated by the krypton 568 flash showing no luminance imbalance induction (B).

END

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